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Imahashi et al.

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[54] **PLASMA PROCESSING APPARATUS**

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[21] Appl. No.: **928,428**

[22] Filed: **Aug. 12, 1992**

[30] **Foreign Application Priority Data**

Aug. 12, 1991 [JP] Japan 3-228270

[51] **Int. Cl.**^{5} **H05H 1/00**

[52] **U.S. Cl.** .... **156/345;** 156/643; 204/298.38; 118/723 R

[58] **Field of Search** 156/345, 643; 118/723; 204/298.16, 298.37, 298.38

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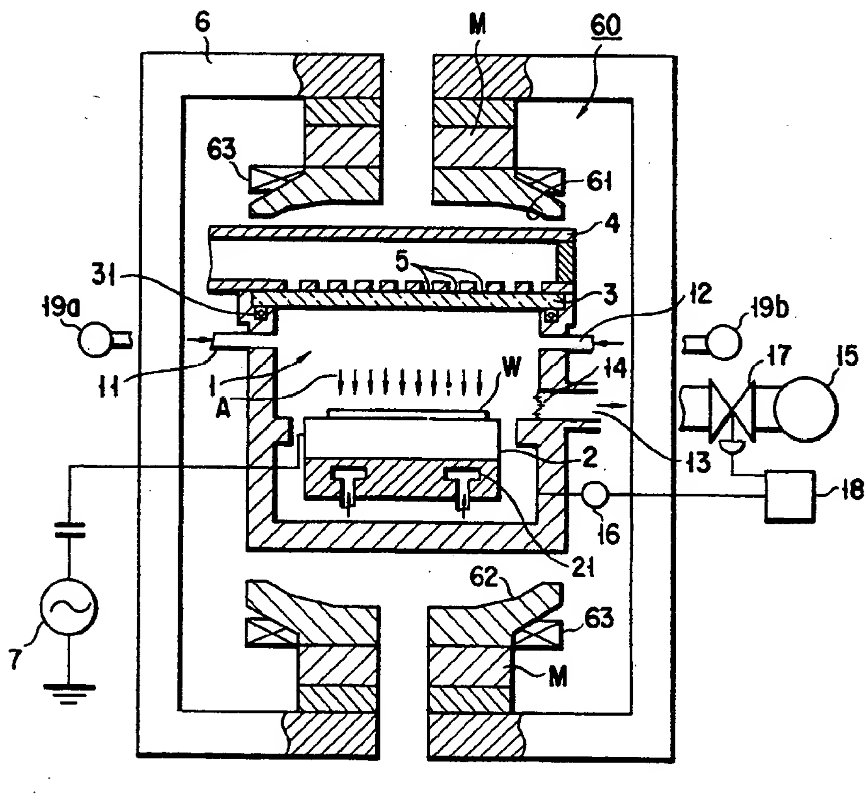
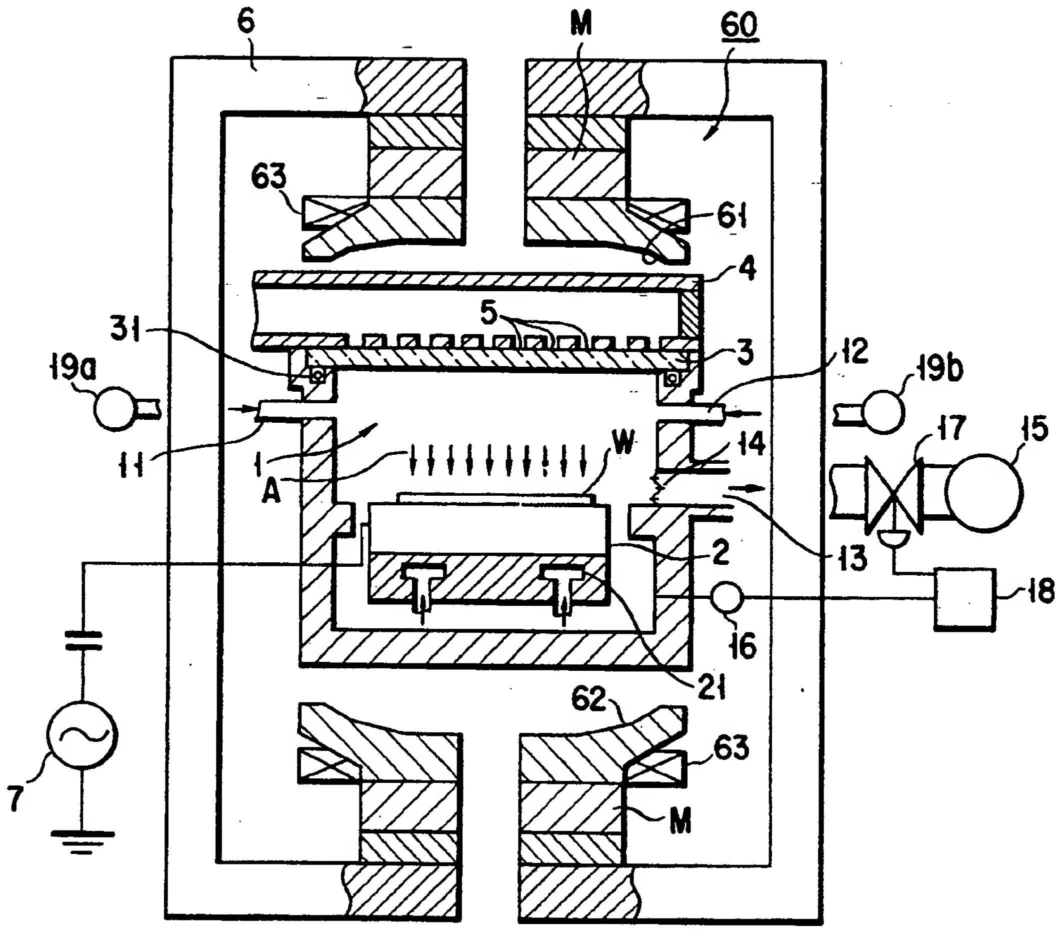
Attorney, Agent, or Firm—Oblon, Spivak, McClelland, Maier & Neustadt

[57] **ABSTRACT**

Microwave inlet ports are formed on a microwave transmission window above a plasma generation chamber. The distance from the microwave inlet ports to a support surface of a wafer support table is set to be an integer multiple of ½ the wavelength of the microwave. Upper and lower magnetic poles opposite to each other are arranged above and below the chamber to form a magnetic field having a uniform strength in the chamber. The strength of the magnetic field is set to be 865 Gauss as a value slightly deviating from 875 Gauss as a value satisfying ideal conditions of an electron cyclotron resonance at a microwave wavelength of 2.45 GHz. The electron energy is suppressed, and damage to the surface of a wafer can be suppressed in wafer surface processing using a plasma.

15 Claims, 6 Drawing Sheets





F I G. 1

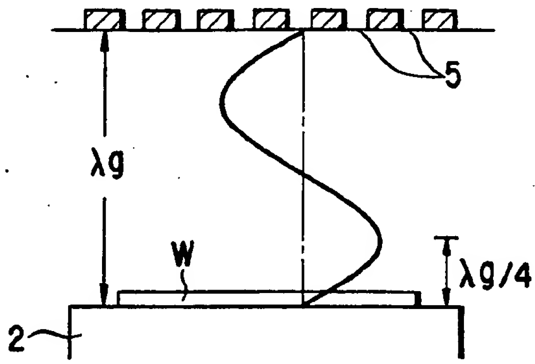

5
λg
W
λg/4
2

FIG. 2

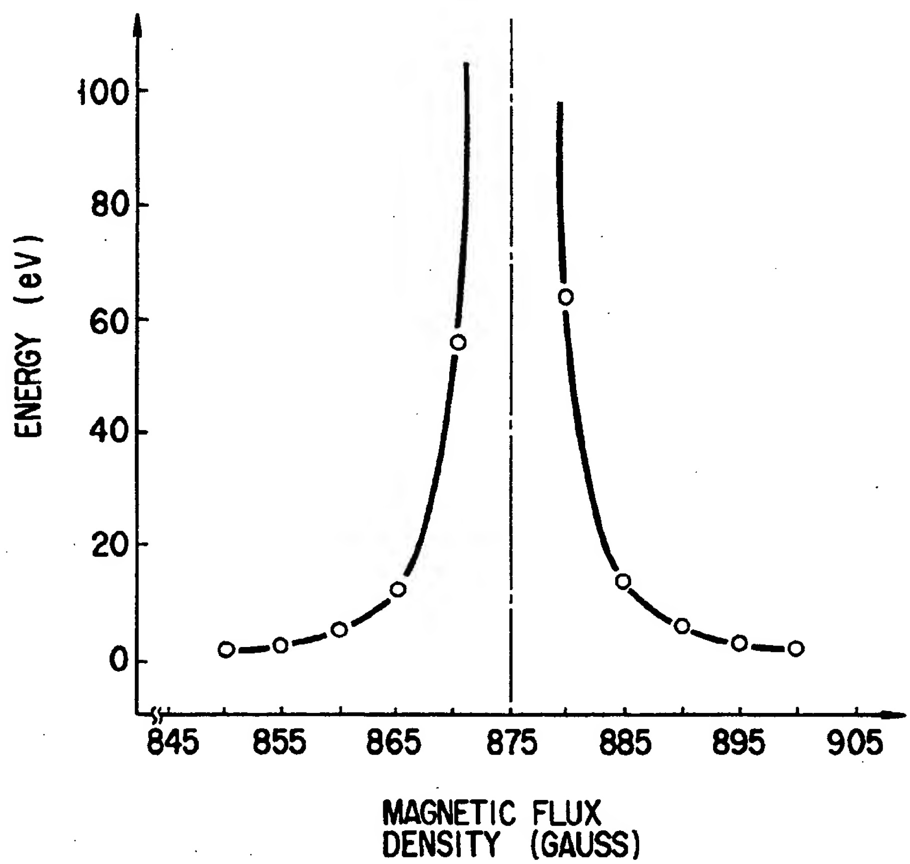

ENERGY (eV)
100
80
60
40
20
0
845
855
865
875
885
895
905
MAGNETIC FLUX
DENSITY (GAUSS)

FIG. 3

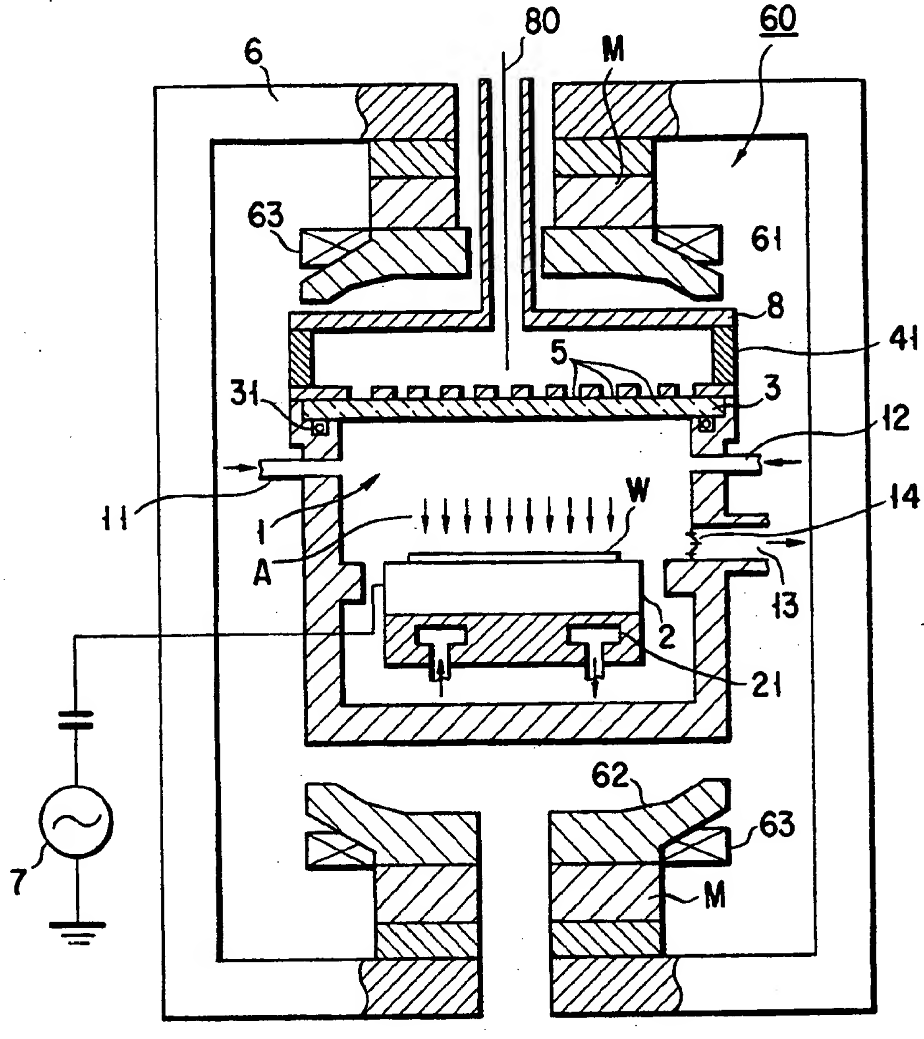


FIG. 4

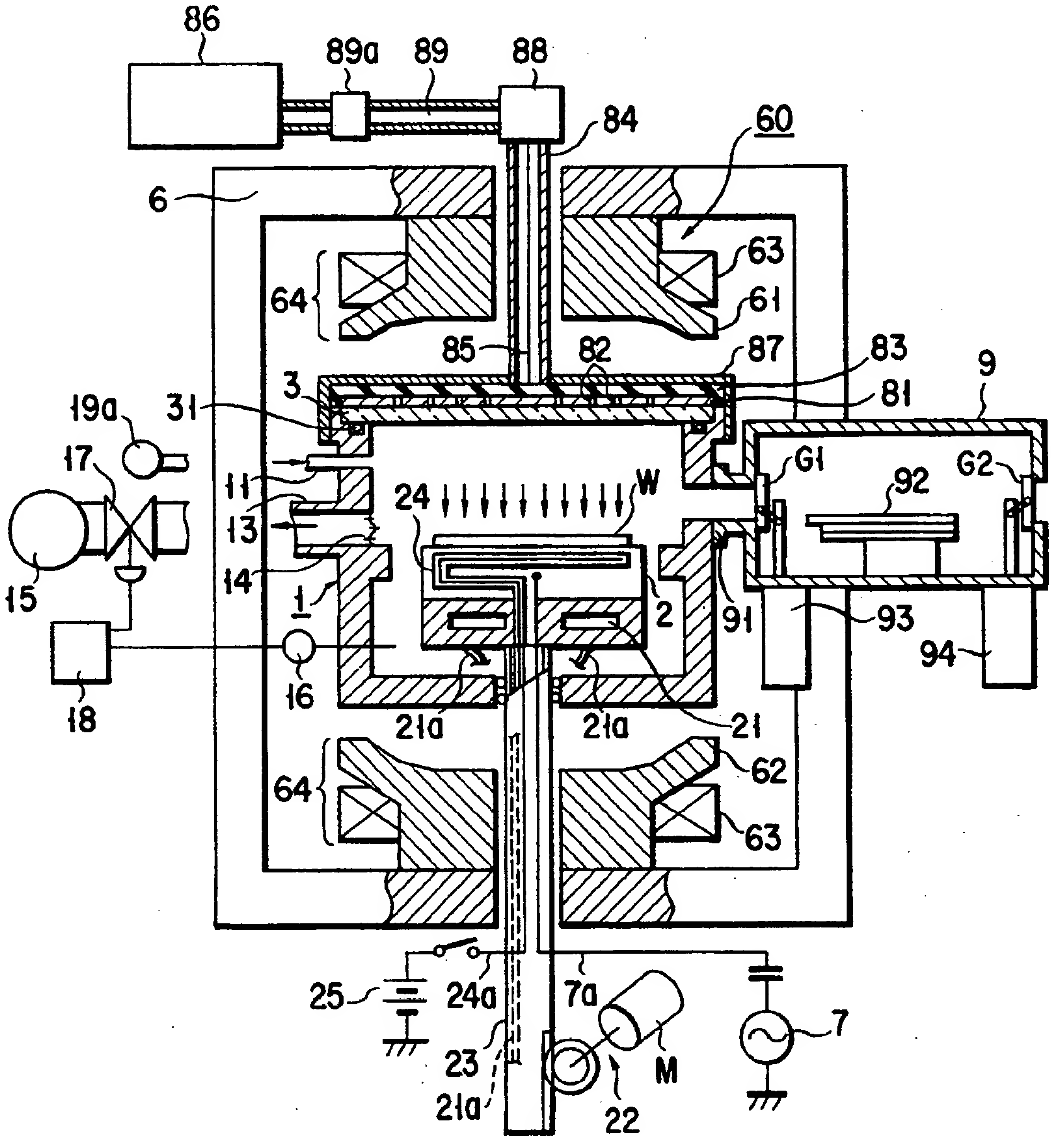

86
89a
89
88
84
60
6
63
64
61
85
82
87
83
9
3
81
31
19a
17
11
G1
G2
92
W
24
13
14
15
1
2
91
93
94
18
16
21a
21a
21
64
62
63
25
24a
7a
7
23
M
21a
22

FIG. 5

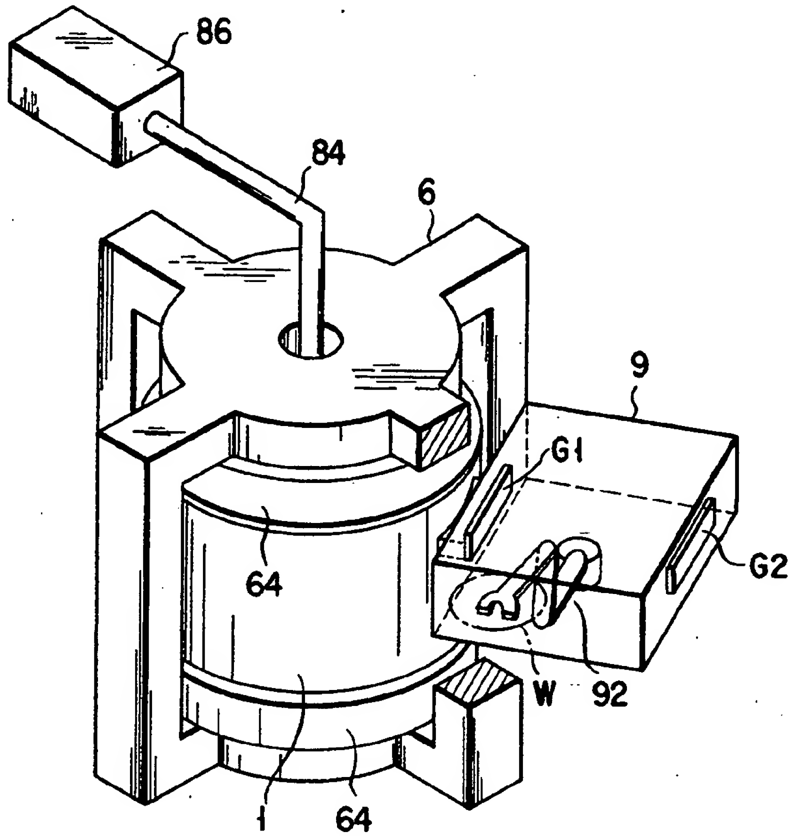


FIG. 6

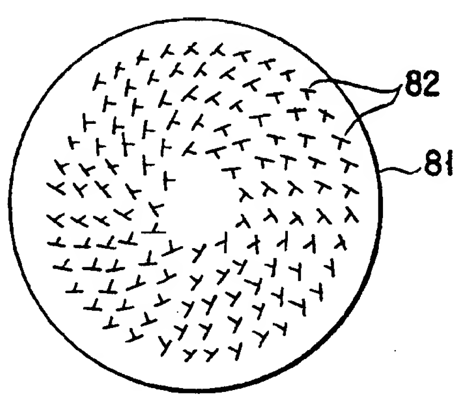


FIG. 7

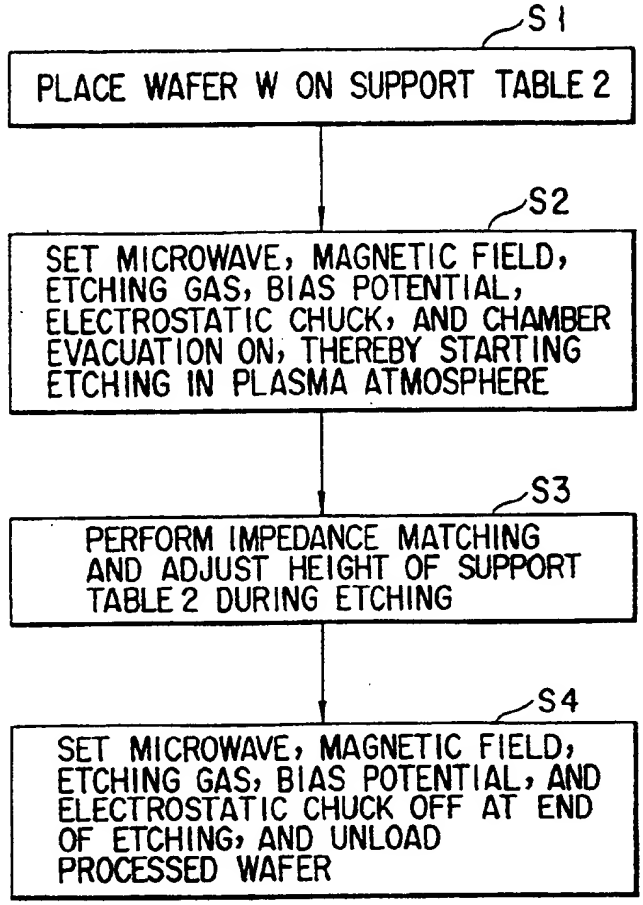

S1
PLACE WAFER W ON SUPPORT TABLE 2
S2
SET MICROWAVE, MAGNETIC FIELD, ETCHING GAS, BIAS POTENTIAL, ELECTROSTATIC CHUCK, AND CHAMBER EVACUATION ON, THEREBY STARTING ETCHING IN PLASMA ATMOSPHERE
S3
PERFORM IMPEDANCE MATCHING AND ADJUST HEIGHT OF SUPPORT TABLE 2 DURING ETCHING
S4
SET MICROWAVE, MAGNETIC FIELD, ETCHING GAS, BIAS POTENTIAL, AND ELECTROSTATIC CHUCK OFF AT END OF ETCHING, AND UNLOAD PROCESSED WAFER

FIG. 8

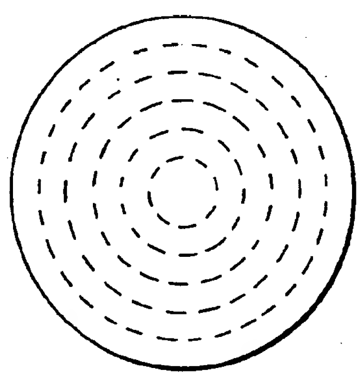


FIG. 9

PLASMA PROCESSING APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a plasma processing apparatus and, more particularly, to a processing apparatus in which a plasma is generated by an electron cyclotron resonance caused by a microwave and a magnetic field and a semiconductor wafer is processed (e.g., etched) by using this generated plasma.

2. Description of the Related Art

In recent years, Since micropatterning of semiconductor devices has been rapidly developed, demands for micropatterning precision, low contamination, less damage, and selectivity in dry-etching techniques have become stricter.

A method of causing a microwave discharge using a resonance phenomenon between an electron cyclotron motion and a microwave in a magnetic field has been recently employed. According to this microwave discharge, since a plasma having a high density can be generated by a non-electrode discharge in a low pressure, a high-speed surface treatment can be performed, and wafers are free from contamination, thus providing industrial advantages.

An example of a conventional plasma processing apparatus of this type is described in Published Examined Japanese Patent Application No. 58-13626. In this disclosed apparatus, a microwave is supplied downward into a plasma generation chamber around which a magnetic field forming means is arranged. A plasma is then generated by an electron cyclotron resonance. Ions in this plasma are extracted by an ion extraction electrode into a processing chamber from the bottom portion of the plasma generation chamber and are radiated on the surface of a target object located inside the processing chamber.

Another example of an apparatus of this type is described in Published Unexamined Japanese Patent Application No. 59-202635. In this disclosed apparatus, a discharge tube constituting a plasma generation chamber has a structure tapered wider from a microwave supply direction to the direction of a target object, and at the same time has a magnetic gradient. Therefore, ions can be transported to the target body and plasma processing in a wide area can be performed.

In the former apparatus, i.e., the apparatus described in Published Examined Japanese Patent Application No. 59-13626, the processing chamber must be arranged independently of the plasma generation chamber, resulting in a bulky apparatus. In addition, since a high voltage of about 1,000 V is required as an ion extraction voltage, the ion energy is high, and the surface of the target object is greatly damaged.

In the latter apparatus, i.e., the apparatus described in Published Unexamined Japanese Patent Application No. 59-202635, since the magnetic gradient is present from the plasma generation region to the surface of the target object, the lines of magnetic force are inclined with respect to the surface of the target object, so that the ions are obliquely incident on the surface of the target object. Therefore, for example, perpendicular etching performance is degraded, and excellent micropatterning becomes difficult.

On the other hand, when a target object is placed in the plasma generation chamber and a magnetic field having a uniform strength is formed in the plasma generation chamber, the separate processing chamber need not be arranged, and ions can be perpendicularly incident on the surface of the target object. In this case, however, the energy (temperature) of the electrons generated by an electron cyclotron resonance phenomenon is extremely increased. In addition, since a probability of collision between electrons and ions is low at a low pressure, the surface of the target object are bombarded with electrons having a high energy to cause a charge-up phenomenon, thereby increasing the floating potential to, e.g., 100 eV. For this reason, when ions pass through an ion sheath, their energy is considerably increased, and the ions having the high energy strike the surface of the target object. In addition to the bombardment with electrons having a high energy, thermal, electrostatic damage to the surface of the target object is increased. The energy of the microwave is absorbed in the target object to undesirably heat the target object to a high temperature.

SUMMARY OF THE INVENTION

It is, therefore, an object of the present invention to suppress damage to the surface of an object to be processed in a plasma processing apparatus in which a plasma is generated by an electron cyclotron resonance caused by a microwave and a magnetic field.

The present invention is based on the findings that when an object to be processed is placed in a plasma generation chamber, a magnetic field having a uniform strength is formed in the plasma generation chamber, and a plasma is generated in conditions slightly deviating from ideal conditions of the electron cyclotron resonance, the electron energy is kept lower in consideration of high-energy electrons which cause damage to the object.

More specifically, according to the present invention, there is provided a method of generating a plasma by an electron cyclotron resonance and processing a substrate by using this plasma, comprising the steps of:

providing a processing chamber having a support surface for supporting the substrate so as to form a discharge space formed above the support table within the chamber;

placing the substrate on the support surface;

setting an interior of the chamber to a vacuum atmosphere;

supplying a processing gas to be converted into the plasma in the chamber;

supplying a microwave to the discharge space; and

forming a magnetic field having a uniform strength in the discharge space, the strength of the magnetic field being set to be a value deviating from ideal conditions of the electron cyclotron resonance by 0.3% to 1.8%.

According to the present invention, since the deviation from the ideal conditions of the electron cyclotron resonance is small, the electron cyclotron resonance phenomenon occurs, but the electron energy can be suppressed compared to the case wherein the ideal conditions of the electron cyclotron resonance are satisfied. As a result, the floating potential is decreased, and the energy of ions which strike the surface of the substrate is set to have an appropriate magnitude, thereby suppressing damage to the surface of the substrate.

Since the distance from the support surface of the support table to a microwave inlet port is set to be an integer multiple of ½ the wavelength of the microwave, the microwave power can be effectively absorbed in the

plasma. Since the microwave is reflected by the support surface, heating of the substrate can be suppressed.

A dielectric body is bonded to the conductive plate having the microwave inlet ports to reduce the distance between the inlet ports, thereby increasing the density of the microwave. Therefore, uniform plasma processing within the surface of the substrate placed opposite to the microwave inlet ports can be performed.

Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate presently preferred embodiments of the invention and, together with the general description given above and the detailed description of the preferred embodiments given below, serve to explain the principles of the invention.

FIG. 1 is a sectional view showing a plasma processing apparatus according to the first embodiment of the present invention;

FIG. 2 is a view for explaining the relationship between the position of the support surface of a wafer support table and the wavelength of a microwave;

FIG. 3 is a graph showing the relationship between the magnetic flux density and the electron energy;

FIG. 4 is a sectional view showing a plasma processing apparatus according to the second embodiment of the present invention;

FIG. 5 is a sectional view showing a plasma processing apparatus according to the third embodiment of the present invention;

FIG. 6 is a perspective view showing the outer appearance of the apparatus shown in FIG. 5;

FIG. 7 is a plan view showing the structure of a metal plate having microwave inlet ports;

FIG. 8 is a schematic flow chart showing an etching process in the apparatus of the third embodiment; and

FIG. 9 is a plan view showing the structure of another metal plate having microwave inlet ports.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a longitudinal sectional view showing a plasma processing apparatus according to the first embodiment of the present invention. Reference numeral **1** denotes a plasma generation chamber for forming a discharge space for generating a plasma by an electron cyclotron resonance. The plasma generation chamber **1** is made of a cylindrical member having a diameter of, e.g., 600 mm, and the wall portion thereof is made of a non-magnetic material such as an aluminum alloy or stainless steel. A conductive wafer support table **2** serving as a support means for supporting a semiconductor wafer W as an object to be processed is disposed at the bottom portion of the chamber 1. The support table **2** electrically floats from the chamber **1**. A coolant path **21** for circulating a coolant such as cooling water for cooling of about −50° C. or liquid nitrogen for cooling of about −150° is formed in the support table **2** to cool the wafer on the support table **2**.

Gas supply pipes **11** and **12** connected to sources **19***a* and **19***b* of etching gases such as Cl_2, SF_4, and CF_4 are connected to the chamber **1**. An exhaust pipe **13** coupled to an evacuating means **15** is connected to the chamber **1** to maintain the interior of the chamber **1** in a predetermined vacuum atmosphere. A pressure gauge **16** is connected to the chamber **1**, and a pressure regulation valve **17** is arranged in the exhaust pipe **13**. The pressure gauge **16** is connected to the pressure regulation valve **17** through a controller **18** in a known manner. The pressure regulation valve **17** is operated by the controller **18** in accordance with an internal pressure of the chamber **1** which is detected by the pressure gauge **16**.

A filter **14** made of a conductive mesh member for shielding a microwave (to be described later) is arranged in the exhaust port of the exhaust pipe **13**. The upper surface of the plasma generation chamber **1** is formed of a microwave transmission window **3** made of, e.g., quartz glass. This window **3** is mounted on the upper end of the wall portion of the chamber **1** with an O-ring **31** interposed.

A rectangular waveguide **4** having a flat hollow structure is disposed above the chamber **1**. This waveguide **4** is connected to a magnetron or microwave generator (corresponding to a portion denoted by reference numeral **86** in FIG. 7) serving as a microwave source. A microwave having a frequency of, e.g., 2.45 GHz is guided from the side portion of the plasma generation apparatus main body to a portion above the chamber **1**. A plurality of slit-like microwave inlet ports **5** are formed in the lower surface of the end portion of the waveguide **4** and face the upper surface of the microwave transmission window **3**. The width of the slit of each inlet port **5** is determined to be, e.g., ($\lambda t/2 \times 1$ cm) if the wavelength of the microwave in the waveguide **4** is defined as λt. A microwave absorbing body **41** for absorbing reflected waves generated in the waveguide **4** is formed at the end face of the waveguide **4**. The absorbing body **41** prevents return of the reflected waves to the magnetron. The absorbing body **41** is cooled to prevent heating of the waveguide **4**.

The region from the microwave inlet ports **5** to the support surface of the wafer support table **2** constitutes a microwave cavity resonator structure. The distance between the microwave inlet ports **5** and the support surface of the wafer support table **2** is determined to be $(\lambda g/2) \times n$ (integer), e.g., $(\lambda g/2) \times 2$ if the wavelength of the microwave supplied from the inlet ports **5** to the chamber **1**, as shown in FIG. 2, is defined as λg. When the above microwave cavity resonator structure is obtained, the microwave power can be more efficiently absorbed in the plasma. In addition, since the support surface of the support table **2** is located at the surface for reflecting the microwave, the support table **2** is not heated by the microwave. Since the power of the microwave absorbed in the wafer is close to zero, an increase in temperature of the wafer by the microwave can also be prevented.

An upper magnetic pole **61** is located above the chamber **1** through the waveguide **4**, and a lower magnetic pole **62** is located below the chamber **1** so as to oppose the upper magnetic pole **61**. The magnetic poles **61** and **62** are coupled by a yoke **6** made of, e.g., soft iron through a permanent magnet M. Magnetic field generation coils **63** are wound around the magnetic poles **61** and **62**, respectively. In this embodiment, the magnetic poles **61** and **62**, the coils **63**, the yoke **6**, and the perma-

nent magnet M constitute a magnetic field forming means **60**. The magnetic flux density of the magnetic field forming means **60** has a uniform magnitude within the plasma generation chamber **1**. The magnetic field forming means **60** generates a downward magnetic field having lines A of magnetic force perpendicular to the surface of a wafer W. The magnetic flux density in the plasma generation chamber **1** is set to be 865 Gauss lower than 875 Gauss which can satisfy the ideal conditions of the electron cyclotron resonance when the frequency of the microwave is set to be, e.g., 2.45 GHz.

The operation of the first embodiment will be described below.

A microwave having a power of, e.g., 800 W and a frequency of, e.g., 2.45 GHz propagates from the magnetron to the waveguide **4** and is supplied from the inlet ports **5** to the chamber **1** through the window **3** in, e.g., a TE mode. Upon excitation of the permanent magnet M and the magnetic field generation coils **63** of the magnetic field forming means **60**, a magnetic field whose magnetic flux density is, e.g., 865 Gauss and the direction of the lines A of magnetic force is downward is generated in a direction perpendicular to the surface of the wafer W on the support table **2** in the chamber **1**.

On the other hand, an etching gas such as chlorine gas is supplied from the gas supply pipes **11** and **12** to the chamber **1** at a flow rate of 10 SCCM. The interior of the chamber **1** is maintained at a pressure of, e.g., about 1×10^{-4} Torr by the evacuating means **15**.

Since the magnitude of the magnetic flux density which satisfies the ideal conditions of the electron cyclotron resonance which correspond to the wavelength of the microwave is 875 Gauss, the magnetic flux density of the field generated in the plasma generation chamber **1** has a slightly smaller value, i.e., 865 Gauss. However, since this difference is very small, an electron cyclotron resonance phenomenon occurs in the chamber **1**. In this embodiment, since the region from the microwave inlet ports **5** to the support surface of the wafer support table **2** serves as the cavity resonator structure, the microwave power can be efficiently absorbed in the electrons, and the energy (temperature) of the electrons is increased. Ions whose energy is increased upon collision with the electrons are accelerated by the floating potential of the wafer W and strike the surface of the wafer W, thereby performing surface processing, e.g., etching.

As described in the "Description of the Related Art", when the magnetic flux density is set to be 875 Gauss, which can satisfy the ideal conditions of the electron cyclotron resonance, the electrons are heated to a high temperature corresponding to an energy of about 100 eV, and the thermal, electrostatic damage to the surface of the wafer is increased. To the contrary, according to the present invention, the magnetic flux density is set to be a value slightly deviating from 875 Gauss, thereby suppressing the damage to the surface of the wafer. The reason for this is surmised as follows.

According to the present invention, the temperature or energy of the electrons is increased by the electron cyclotron resonance phenomenon. Since the relationship between the magnetic flux density and the frequency of the microwave is shifted from the ideal conditions of the electron cyclotron resonance, the energy of the electrons is increased to a value between 10 and 20 eV and is then decreased. This increase/decrease cycle is repeated. For this reason, the temperature of the electrons is not extremely increased but is kept to be a small value. As a result, even if the surface of the wafer is charged up by the electrons, since the floating potential of the wafer is low, the energy of the ions to strike the surface of the wafer is lowered but is still high enough to perform the surface processing.

The intensity of the plasma is maximized at two positions spaced apart from the support table **2** upward by $(\frac{1}{4}\times\lambda g)$ and $(\frac{3}{4}\times\lambda g)$. However, when the window **3** is located at a position above the support table **2** by $(\frac{1}{2}\times\lambda g)$, the position of the maximum intensity of the plasma is limited to only one position above the support table **2**, thus forming a planar plasma on the surface of the wafer and hence performing good surface processing. In this case, although the position of the maximum intensity of the plasma is located near the wafer, thermal, electrostatic damage to the wafer can be prevented due to the low temperature of the electrons described above.

When the microwave power is further increased, a probability of collision between electrons and ions tends to increase. In order to set the electron temperature and the collision probability to appropriate values, the deviation from the ideal conditions of the electron cyclotron resonance and the microwave power are appropriately selected.

In the first embodiment, an RF power source **7** may be connected, as shown in FIG. **1**, to apply a bias potential to the support table **2**. In this case, ion extraction can be further efficiently performed.

In order to examine an appropriate deviation from the ideal conditions of the electron cyclotron resonance so as to examine the relationship between the magnetic flux density and the microwave frequency, energy values (temperature values) of electrons in a plasma as a function of the magnitude of the magnetic flux density are numerically calculated using an electron cyclotron motion equation at a microwave frequency of 2.45 GHz. The calculation results are shown in FIG. **3**.

Judging from these results, the appropriate range of magnetic flux density deviations from the ideal conditions is ±0.3% to ±1.8% with respect to 875 Gauss as the center which satisfies the ideal conditions of the electron cyclotron resonance. In consideration of a more preferable electron energy range being about 10 ev to about 60 eV, the preferable range of the magnetic flux density deviations from the ideal conditions is assumed to be ±0.5% to ±1.5% with respect to 875 Gauss as the center. The above range is derived in consideration of the following three points. As is apparent from FIG. **3**, when the magnetic flux density is set to be 875 Gauss which can satisfy the ideal conditions of the electron cyclotron resonance, the electron energy is infinitely large. However, when the magnetic flux density is set to be 875 Gauss, electrons actually collide against gas molecules and atoms, and the kinetic energy of the electrons is decreased. In practice, the electron energy is not infinitely large but is set to be about 100 eV. The electron temperature which allows good surface processing without damaging the wafer corresponds to an electron energy falling within the range of about 8 ev to about 80 ev.

The deviation from the ideal conditions of the electron cyclotron resonance is changed in accordance with changes in apparatus structure, but does not include a case in which the electron cyclotron resonance phenomenon does not occur at all.

FIG. **4** is a longitudinal sectional view of a plasma processing apparatus according to the second embodi-

ment of the present invention. The same reference numerals in FIG. 4 denote the same parts as in the first embodiment of FIG. 1, and a detailed description thereof will be omitted.

The second embodiment is different from the first embodiment in that a microwave is not supplied from the side of the apparatus main body but from the upper side. More specifically, a radial waveguide 8 is located above a chamber 1. A plurality of slit-like microwave inlet ports 5 are formed in the bottom surface of the waveguide 8 in the same manner as in the first embodiment. The microwave inlet ports 5 oppose the upper surface of a microwave transmission window 3. A coaxial cable 80 is inserted into the central opening of the upper surface of the waveguide 8. The coaxial cable 80 is connected to a magnetron or microwave generator (corresponding to a portion denoted by reference numeral 86 in FIG. 7) serving as a microwave source. In this embodiment, a yoke 6 for connecting upper and lower magnetic poles 61 and 62 is divided into four parts symmetrical about the vertical central line of the apparatus.

FIG. 5 is a longitudinal sectional view showing a plasma processing apparatus according to the third embodiment of the present invention, and FIG. 6 is a sectional view thereof. The same reference numerals in FIGS. 5 and 6 denote the same parts as in the first embodiment of FIG. 1, and a detailed description thereof will be omitted.

In this embodiment, a yoke 6 is divided into four parts symmetrical about the vertical central line, and at the same time, a corner portion of each of the four divided parts has a rectangular planar shape. In this case, even if the yoke 6 is not spread outward, the sectional area of the yoke 6 can be large, so that a high magnetic flux density can be obtained.

In this embodiment, no permanent magnets are used in the upper and lower sides of the yoke 6. Upper and lower magnetic poles 61 and 62 are arranged, and coils 63 are wound therearound to constitute an electromagnet 64. In this manner, when a magnetic field is generated by only the electromagnet 64, the strength of the magnetic field can be controlled by the magnitude of current supplied to coils 63, so that the conditions can be easily set and assembly is also facilitated.

A metal plate 81 as a conductive member is arranged on the upper surface of a microwave transmission window 3. The metal plate 81 has T-shaped slits 82 serving as microwave inlet ports along a spiral line, as shown in FIG. 7. A ceramic plate 83 is bonded to the upper surface of the metal plate 81. The ceramic plate 83 is covered with a metal plate 87. The metal plates 81 and 87 are insulated from each other through the ceramic plate 83.

One end of a coaxial cable or line 84 is guided to the central portion of the upper surface of the ceramic plate 83 serving as a dielectric body through holes formed in the centers of the yoke 6 and the electromagnet 64. The outer conductive pipe of the line 84 is connected to the outer metal plate 87 which covers the ceramic plate 83. A central conductor 85 of the line 84 extends through the ceramic plate 83 and is brought into contact with the surface of the metal plate 81. A coaxial converter 88 is arranged at the upper end portion of the coaxial line 84, and a waveguide 89 is connected thereto at one end. The waveguide 89 is connected at the other end to a microwave generator 86 located above the yoke 6. A tuner 89a for adjusting impedance matching is arranged in the waveguide 89.

The dielectric constant of the ceramic is about 9, and the wavelength of the microwave propagating through the ceramic is about $\frac{1}{3}$ that propagating in air. When the ceramic plate 83 is arranged on the metal plate 81 as described above, the pitch of the slits 82 of the metal plate 81 can be reduced. That is, the density of the slits 82 can be increased, so that uniform plasma processing can be performed on a wafer W. Since the lower end of the internal or central conductor 85 is in contact with the metal plate 81, no discharge occurs between the conductor 85 and the metal plate 81.

The end of the central conductor of the coaxial cable or line 84 need not be connected to the metal plate 81, but must be connected to at least the ceramic plate 83. For example, the central conductor extends into the ceramic plate 83 or is brought into contact with the surface of the ceramic plate 83.

A lifting mechanism 22 as a combination of a pinion-rack mechanism and a motor M for lifting a wafer support table 2 is located below the yoke 6. A lifting rod 23 extends through the holes in the central portions of the yoke 6 and the electromagnet 64. The upper end of the lifting rod 23 is connected to the support table 2. The support table 2 is vertically moved by the lifting mechanism 22 to load or unload the wafer W or adjust the distance between the metal plate 81 and the support table 2. An electrostatic chuck 24 is disposed on the upper surface of the wafer support table 2 to support and hold the wafer W. The electrostatic chuck 24 is connected to a DC power source 25 through a power supply line below the support table 2. The DC power source 25 is located outside the chamber 1.

The lifting rod 23 has a hollow structure. All of wiring lines 24a for the electrostatic chuck 24, wiring lines 7a of an RF power source 7 for applying a bias potential to the support table 2, and a line 21a for supplying a coolant to a coolant path 21 pass through the lifting rod 23 and are guided to the support table 2. With this structure, the vertical movement of the support table 2 can be smoothly performed.

A load lock chamber 9 is hermetically coupled to a plasma generation chamber 1 with an O-ring 91 interposed. A convey mechanism 92 for the wafer W, which is constituted by, e.g., an articulated arm, is arranged inside the load lock chamber 9. The load lock chamber 9 has gates G1 and G2 for opening or closing an opening portion between the load lock chamber 9 and the plasma generation chamber 1 and an opening portion between the load lock chamber 9 and the outer atmosphere. Reference numerals 93 and 94 denote drive mechanisms for driving the gates G1 and G2, respectively.

The etching process of the semiconductor wafer by using the apparatus (FIG. 5) of the third embodiment will be described with reference to a flow chart in FIG. 8.

Step S1: After a wafer is loaded in the load lock chamber 9, the chamber 9 is set in the same vacuum state as that of the plasma generation chamber 1. The gate G1 is opened, and the wafer W is placed on the support table 2.

Step S2: A microwave having, e.g., a power of 800 W and a frequency of 2.45 GHz is supplied from the microwave generator 86. A magnetic field, whose magnetic flux density falls within the range of 895 Gauss q 0.1 to 1.5%, e.g., 865 Gauss and lines of magnetic forces are

directed downward, is formed by a magnetic field forming means **60**. Meanwhile, an etching gas such as chlorine gas is supplied from gas supply pipes **11** and **12** to the chamber **1** at a flow rate of 10 SCCM. At the same time, the internal pressure of the chamber **1** is maintained at, e.g., 1×10^{-4} Torr by an evacuating means **15**. An RF bias potential is supplied from the power source **7** to the support table **2**, and at the same time, the electrostatic chuck **24** is turned on.

Since the magnetic flux density which satisfies the ideal conditions of the electron cyclotron resonance corresponding to the microwave frequency is 875 Gauss, the magnetic flux density of the magnetic field formed within the plasma generation chamber **1** is slightly lower (e.g., 865 Gauss) than the density satisfying the ideal conditions. However, since this difference is very small, an electron cyclotron resonance phenomenon occurs in the chamber **1**. In this embodiment, since the region from the microwave inlet ports **5** to the support surface of the wafer support table **2** serves as the cavity resonator structure, the microwave power can be efficiently absorbed in the electrons, and the energy (temperature) of the electrons is increased. Ions whose energy is increased upon collision with the electrons are accelerated by the floating potential of the wafer W and strike the surface of the wafer W, thereby performing surface processing, e.g., etching.

Step S3: At the start of or during etching processing, the tuner **89***a* is operated to minimize the reflection of the microwaves to perform impedance matching. In addition, the lifting mechanism **22** is operated to adjust the height of the support table **2**, as needed, thereby changing the degree of reflection of the microwaves. This adjustment can be performed in accordance with a desired mode of etching processing. For example, the adjustment may be performed to minimize the reflection of the microwaves or slightly increase the reflection.

Step S4: When etching is performed for a predetermined period of time, supply of the microwave, magnetic field, bias potential, and etching gas is stopped, and the electrostatic chuck is dissolved. After the gas in the chamber **1** is sufficiently exhausted, the processed wafer W is unloaded through the load lock chamber **9**, and the next wafer processing is started.

The present invention is not limited to microwave reflection on the support surface of the support table. For example, in order to reflect a microwave on the surface of, e.g., the wafer, the distance from the surface of the wafer to the microwave inlet ports may be set to be an integer multiple of ½ the wavelength of the microwave. In this case, even if an object to be processed is thick, absorption of the microwave power by the object can be prevented, resulting in convenience.

According to the present invention, a microwave antenna formed of a conductive plate as a disc-like metal plate and bonded to a dielectric body, e.g., a ceramic plate may be arranged in the plasma generation chamber **1**. This conductive plate has a diameter of, e.g., 500 mm and a thickness of, e.g., 0.3 mm, which is sufficiently large conductor with respect to the wavelength of the microwave. Slots (elongated holes) serving as microwave inlet ports and having a length of ½ the in-tube wavelength of the microwave are formed in the conductive plate. Specifically, the slots may have a length of about 2 cm, and a width of from 1 to 5 mm, and arranged coaxially, as shown in FIG. **9**.

The present invention is applicable to an ECR plasma processing apparatus having a structure in which a microwave is not reflected by a support table or a target object. The present invention is also applicable to various plasma surface processing operations such as etching, ashing, and CVD. In this case, it is preferable to provide an implementation such as addition of a structure for heating or cooling a support table.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, representative devices, and illustrated examples shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.

What is claimed is:

1. An apparatus for generating a plasma by an electron cyclotron resonance and processing a substrate by using this plasma, comprising:
   - a processing chamber;
   - means for setting said chamber in a vacuum atmosphere;
   - a support table disposed in said chamber, said support table having a support surface for supporting the substrate, and said chamber defining a discharge space above said support surface;
   - gas supplying means for supplying a processing gas to be converted into the plasma in said chamber;
   - first and second magnetic poles respectively located on upper and lower sides of the discharge space, and both located outside said chamber, in order to form a magnetic field in the discharge space;
   - means for adjusting the strength of the magnetic field;
   - a microwave transmission window formed in said chamber to oppose the discharge space;
   - a first conductive plate arranged on said microwave transmission window outside said chamber,
   - a plurality of slits formed in said first conductive plate and serving as microwave inlet ports;
   - a dielectric plate adjoining said first conductive plate;
   - a second conductive plate adjoining said dielectric plate with no gap therebetween; and
   - microwave supply means for supplying a microwave to said first conductive plate, and comprising a coaxial line constituted by a central conductor and an outer conductive pipe, an end of said central conductor being guided to a central portion of an upper surface of said dielectric plate without contacting said second conductive plate so as to form transmission paths of the microwave from the central portion to peripheral portions in said dielectric plate.

2. An apparatus according to claim **1**, wherein said central conductor penetrates said dielectric plate and is connected to said first conductive plate, and said outer conductive pipe is connected to said second conductive plate.

3. An apparatus according to claim **1**, wherein said microwave inlet ports are located opposite to said support surface, and a distance from said support surface or a surface of said substrate to said microwave inlet ports is set to be an integer multiple of ½ a wavelength of the microwave.

4. An apparatus according to claim **1**, wherein said dielectric plate essentially consists of a ceramic material.

5. An apparatus according to claim 2, wherein said coaxial line is connected to a microwave generator through a coaxial converter and a waveguide.

6. An apparatus according to claim 5, wherein a tuner for adjusting impedance matching is arranged in said waveguide.

7. An apparatus according to claim 3, wherein said support surface is formed to support a semiconductor wafer.

8. An apparatus according to claim 7, wherein said gas supply means comprises etching gas supply means.

9. An apparatus according to claim 8, further comprising means for applying an RF bias potential to said support surface, said support surface being constituted by a conductor.

10. An apparatus according to claim 8, wherein a coolant path for cooling said support surface is arranged in said support table.

11. An apparatus according to claim 9, wherein electrostatic chuck means for fixing the wafer on said support surface is arranged in said support table.

12. An apparatus according to claim 7, further comprising lift means for vertically moving said support table.

13. An apparatus according to claim 12, further comprising means for applying an RF bias potential to said support surface, said support surface being constituted by a conductor, a coolant path, formed in said support table, for cooling said support surface, and electrostatic chuck means for fixing the wafer on said support surface, and wherein said lift means comprises a hollow lifting rod extending through said chamber, said bias potential applying means, said coolant path, and said electrostatic chuck means communicating with associated members outside said chamber through said hollow lifting rod.

14. An apparatus according to claim 1, wherein said support table is conductive and is electrically isolated from the chamber.

15. An apparatus according to claim 1, wherein said slits comprise T-shaped slits and are arranged along a spiral line.

* * * * *

US005861601A

United States Patent [19]

Sato et al.

[11] **Patent Number: 5,861,601**

[45] **Date of Patent: Jan. 19, 1999**

[54] **MICROWAVE PLASMA PROCESSING APPARATUS AND METHOD**

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[73] Assignee: **Hitachi, Ltd.**, Tokyo, Japan

[21] Appl. No.: **340,337**

[22] Filed: **Nov. 14, 1994**

[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**^{6} **B23K 10/00**

[52] **U.S. Cl.** **219/121.43**; 219/121.41; 204/298.37; 156/345

[58] **Field of Search** 219/121.43, 121.44, 219/121.59, 121.41, 121.36; 204/298.17, 298.18, 298.35, 298.37; 156/345

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Primary Examiner—Mark H. Paschall
Attorney, Agent, or Firm—Antonelli, Terry, Stout & Kraus, LLP

[57] **ABSTRACT**

The present invention relates to a microwave plasma processing apparatus, suited for generating a plasma by using microwaves, and a processing method. Microwaves propagated through a circular waveguide are tuned in the space thereof by a microwave tuner that is installed to match the impedance, and are introduced in a uniform and most efficient state into a discharge block having a plasma-resistant inner surface that is enlarged in a tapered form through a microwave introduction window. Then, a processing gas controlled to a predetermined pressure by a gas supplying structure and gas evacuating structure is turned into a plasma which is more uniform and is more dense by interaction of a microwave electric field that is efficiently introduced and a magnetic field produced by a solenoid coil.

2 Claims, 3 Drawing Sheets

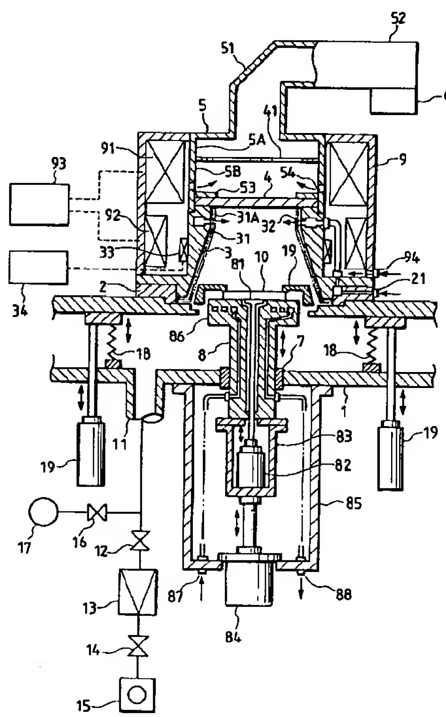

FIG. 1

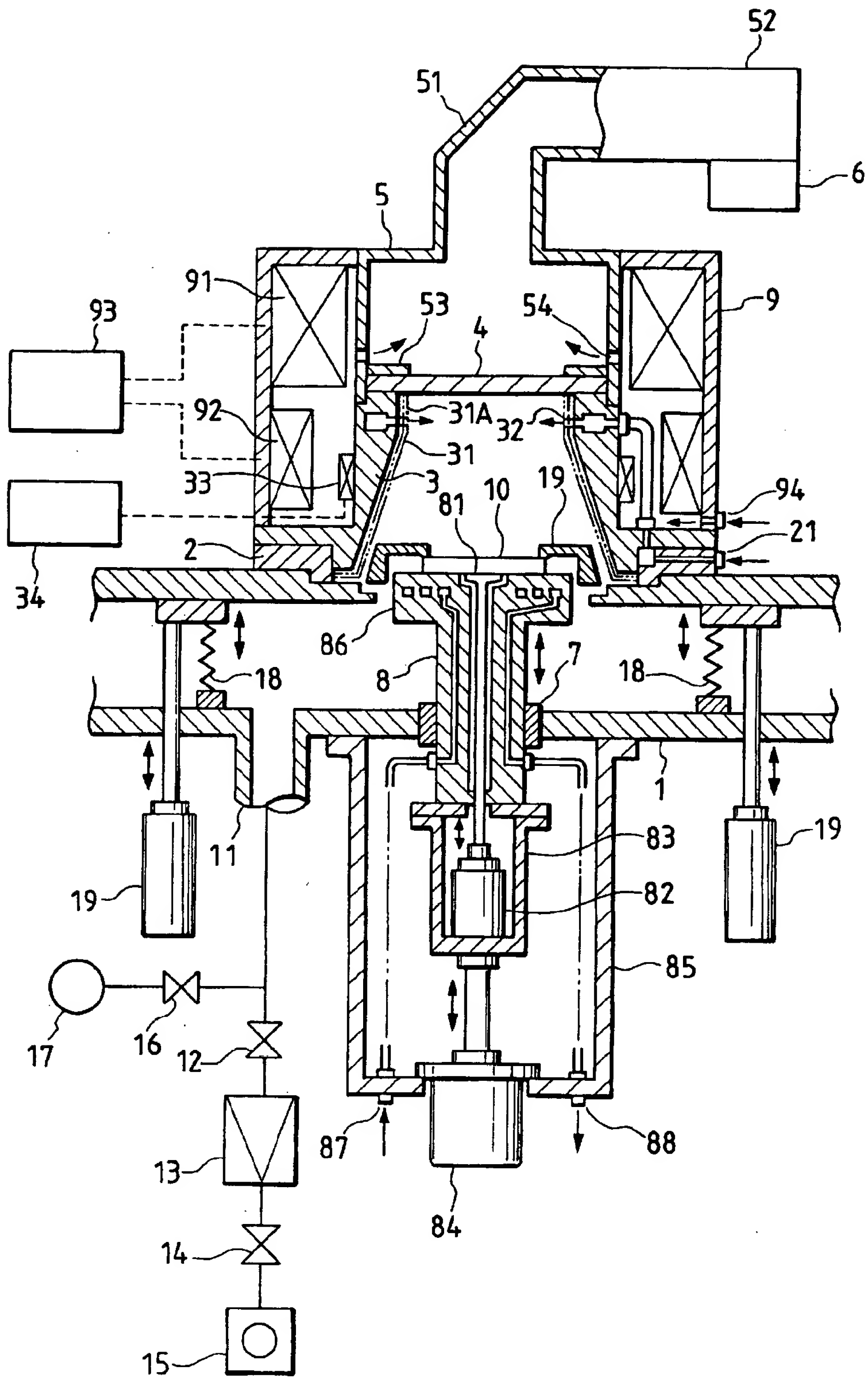
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FIG. 2

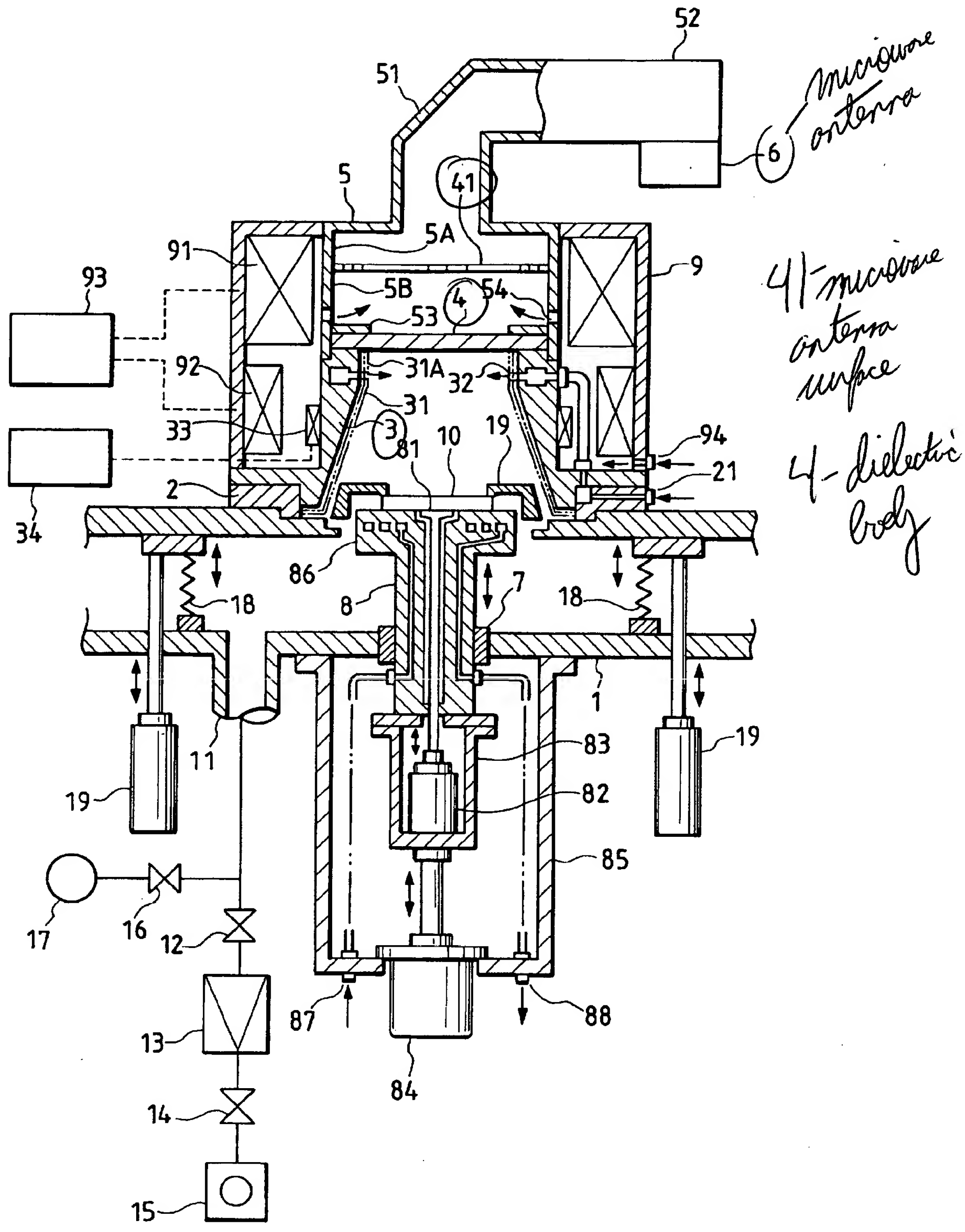
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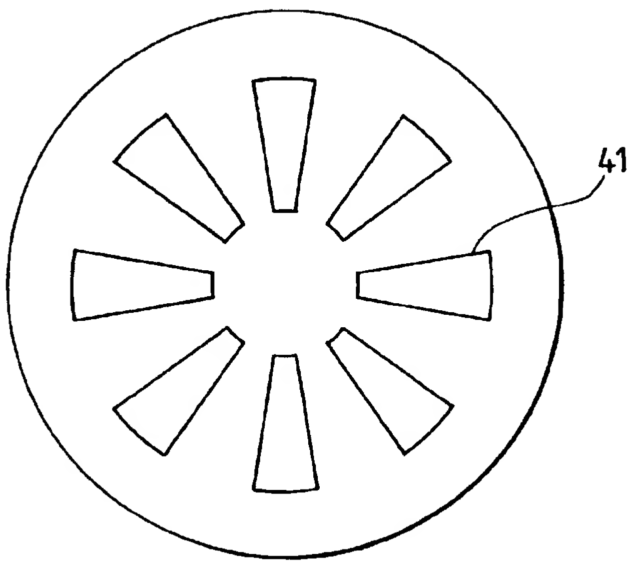
FIG. 3



MICROWAVE PLASMA PROCESSING APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to a microwave plasma processing apparatus and a processing method. More particularly, it relates to a microwave plasma processing apparatus and a processing method which are well suited for generating a plasma by use of microwaves and subjecting samples such as semiconductor device substrates, etc. to a plasma processing such as an etching process, a film forming process, etc.

2. Description of the Prior Art

As a conventional microwave plasma processing apparatus, the one disclosed in, for example, Japanese Patent Laid-Open No. 133322/1992 is known. The apparatus is such that the waveguide has a nearly cylindrical shape, a discharge chamber connected to the waveguide via a gas-tight microwave transmission window is formed into a discharge block made of a hollow cylindrical electrically conductive material that is enlarged in a taper in the direction in which the microwaves travel, and a plasma of a high density is generated by the interaction of a magnetic field generated in a discharge chamber by an air-core coil provided on the outside of the discharge block and a microwave electric field introduced into the discharge chamber via the waveguide, in order to enhance uniformity of the processing.

The above-mentioned prior art, however, does not pay attention to the mode of the microwaves introduced into the discharge chamber, the plasma resistance of the inner wall of the discharge chamber, and change in the process characteristics during continuous processing. That is, attention has not been paid sufficiently to introduction the lines of electric force of microwaves propagated through the waveguide into the discharge chamber of and, besides, the uniformity of plasma and the plasma generation efficiency are not satisfactory. According to the prior art, furthermore, the discharge block is made of a nonmagnetic electrically conductive material such as aluminum. When the material to be processed is of Al or an Al alloy, a halogen gas is used as the etching gas. When such a gas is turned into a plasma, not only the material to be processed but also the inner wall surfaces of the discharge block constituting the discharge chamber are etched by active species in the plasma. Besides, the processing changes with time due to a rise in the temperature of the discharge block of the plasma generation chamber during the processing with plasma and due to the adhesion of reaction products generated during the processing with the plasma.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a microwave plasma processing apparatus wherein the microwave mode introduced into the discharge chamber can be optimized and a uniform plasma of a high density can be produced.

Another object of the present invention is to provide a microwave plasma processing apparatus by use of which even a material that uses a halogen gas can be processed with plasma without permitting the discharge block to be etched.

A further object of the present invention is to provide a microwave plasma processing apparatus and a processing method capable of stably executing the processing with a plasma maintaining a good state without any change in the processing performance with the passage of time even when a material to be processed is continuously processed.

The above-mentioned object is accomplished by a microwave plasma processing apparatus comprising:

- a sample stage on which is placed a substrate to be processed;
- a processing chamber which contains therein the sample stage and has an opening facing the surface of the sample stage on which is placed the substrate to be processed;
- a discharge block of a hollow cylinder made of a non-magnetic electrically conductive material that is mounted on the outside of the opening of the processing chamber, and having an inner surface that is tapered to enlarge toward the sample stage;
- a circular waveguide that is connected, via a microwave introduction window, to an opening at the other end of the discharge block;
- a tuning means which is provided in the circular waveguide to tune the microwaves;
- a solenoid coil provided on the outside of said discharge block;
- a gas feeding means for feeding a processing gas into the discharge block; and
- an evacuation means for evacuating the interior of the processing chamber to a predetermined pressure.

The above-mentioned another object is accomplished by forming a plasma-resistant protective member on the inner wall surface of the discharge block.

The above-mentioned further object is accomplished by providing the discharge block with a heater of which the temperature can be adjusted and by employing a method wherein:

- a substrate to be processed is processed with a plasma while keeping a plasma generation chamber at a predetermined constant temperature;
- after the substrate to be processed is processed with a plasma and is transferred from the processing chamber, the interior of the processing chamber is cleaned with a plasma without placing any substrate to be processed on the sample stage;
- a new substrate to be processed is transferred into the processing chamber after the cleaning with a plasma has been finished; and

the new substrate to be processed is then processed.

The operation of the invention will be described below.

Microwaves propagated through the circular waveguide are tuned in the space thereof by a tuning means the shape of which is set optimally for the impedance matching, introduced in a uniform and most efficient state into the discharge block through a microwave introduction window, and a processing gas controlled to a predetermined pressure by a gas feeding means and an evacuating means is turned into a plasma uniformly at a high density by the interaction of a microwave electric field that is efficiently introduced and a magnetic field produced by a solenoid coil. This makes it possible to further improve the processing performance.

By the provision of a protective member formed on the inner wall surface of the discharge block, furthermore, the discharge block is not etched even when a material to be processed of the same material of the discharge block is processed with a plasma generated in the discharge block. Therefore, the processing with a plasma is carried out with a good processing performance independently of the material that is to be processed.

Moreover, by providing the discharge block with a heater of which the temperature can be adjusted and by employing a method wherein a substrate to be processed is processed with a plasma while keeping a plasma generation chamber at a predetermined constant temperature; after the substrate to be processed is processed with a plasma and is transferred from the processing chamber, the interior of the processing chamber is cleaned with a plasma without placing any substrate to be processed on a sample stage; a new substrate to be processed is introduced into the processing chamber after the cleaning with a plasma has been finished; and the new substrate to be processed is then processed, the processing chamber can be kept clean and stable plasma processing can be continuously performed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a vertical sectional view illustrating a microwave plasma processing apparatus of an embodiment of the present invention;

FIG. 2 is a vertical sectional view illustrating a microwave plasma processing apparatus of another embodiment of the present invention; and

FIG. 3 is a plan view of a slot antenna of FIG. 2.

DESCRIPTION OF THE EMBODIMENTS

An embodiment of the present invention will now be described with reference to FIG. 1.

FIG. 1 is a diagram illustrating the structure of a microwave plasma processing apparatus. This is the case where the apparatus is used for etching which is a processing with a plasma.

In FIG. 1, a processing chamber 1 is a container made of, for example, stainless steel and has a space therein. The processing chamber 1 has a circular opening in an upper portion thereof and an exhaust port 11 formed in a lower portion thereof. An evacuation means is connected to the exhaust port 11. The evacuation means in this case comprises a pressure control valve 12, a turbo molecular pump 13, a hot valve 14 and a rotary pump 15, which are connected to the exhaust port 11 in the order mentioned via a piping. A pressure detector 17 (Penning gage in this case) for detecting a high degree of vacuum is attached, via a valve 16, to the exhaust port 11 before the pressure control valve 12. Moreover, a diaphragm vacuum gage (not shown) for detecting the pressure during the processing is attached to the exhaust port 11 before the pressure control valve 12. The internal space of the processing chamber 1 is partitioned by sluice valves 18 made up of bellows. To the sluice valves 18 are coupled lift drive units 19.

The opening at the upper portion of the processing chamber 1 is provided with a support, and a wafer holder 19 is placed and held on the support. The wafer holder 19 on the support may be of the mechanical type like this mechanism or may be of an electrostatic attraction type which electrically secures the wafer.

A hollow cylindrical discharge block 3 is gas-tightly mounted to the opening at the upper portion of the processing chamber 1 via a ring-like base flange 2. The discharge block 3 has an inner surface that is tapered to enlarge downward (in the drawing) at an angle of 10° to 30° with respect to the axial direction, and has, in this case, a plurality (20–50) of gas blowing ports 32 that are evenly formed along the circumference of the inner surface at an upper portion thereof (in the drawing). The inner surface of the discharge block 3 is tapered, so that the plasma is uniformly diffused to uniformly process the substrate that is to be processed. The angle of taper is preferably small, so that the mode of electric field does not change or other electric field modes does not increasingly enter while the microwaves travel through the discharge block 3. When the microwave electric field is of mode TE_{11} or mode approximate thereto, the size of the tapered angle is desirably from 1.5 to 2.0 D in a position of the substrate to be processed, from 0.5 to 1.5 D in a position of the microwave introduction window, and the height therebetween is from 1.0 to 1.5 D, where D is the diameter of the substrate. The discharge block 3 is made of a non-magnetic electrically conductive material such as aluminum, non-magnetic stainless steel or the like. A protective member which is a plasma-resistant material is formed on the inner surface of the discharge block 3. The plasma-resistant material refers to the one that is little etched by the active species in a plasma. For instance, the material is alumina, mullite (Al_2O_3+SiO_2), quartz or the like. In this case, a protective film 31 is formed as the protective member. Further, a quartz sleeve 31A is inserted in the inner wall of the protective film 31. A heater 33 and a thermocouple (not shown) are mounted on the outer peripheral surface of the discharge block 3 in contact—with the surface, and the discharge block 3 is heated at a temperature of about 120° C. by a controller 34 that is connected to the heater 33 and to the thermocouple. In the opening at the upper portion of the discharge block 3 is gas-tightly mounted a disk-like microwave introduction window 4 made of a material which transmits microwaves such as quartz, alumina or the like, and a plasma-generating space is gas-tightly kept in the processing chamber 1 and in the discharge block 3 communicating with the chamber 1. Chamber 1 utilizes a chamber wall construction that includes application of a protective film or quartz in order to prevent the inside surface of the chamber wall being damaged by plasma ions and radicals.

A circular waveguide 5 is connected to the microwave introduction window 4. To the other end of the circular waveguide 5 are connected a rectangular-circular conversion waveguide 51 and a rectangular waveguide 52 in this order, and a microwave oscillator 6 is attached to the end of the rectangular waveguide 52. In the circular waveguide 5 is provided a tuning means for tuning microwaves to provide a fixed mode such as TE_{11} mode under the resonant condition in the circular waveguide 5 having a resonation function. The tuning means also acts to select a desired mode to be transferred to the discharge chamber. Here, the tuning means referred to is a means that decreases the amount of reflection of the microwaves. In this case, the tuning means is a microwave tuning plate 53 of a ring-like disk and is mounted on an upper portion of the microwave introduction window 4. The tuning means is a plate having an opening through which the microwaves pass, and an optimum shape of the opening depends upon the mode of the microwave electric field transferred to the discharge chamber. In the case of mode TE_{11} or a mode approximate thereto, a non-circular shape such as an oval shape or the like shape is preferable. If TE_{01} mode is elected a circular shape may be effective. By employing an optimal shape of the microwave tuning plate that matches the mode of the microwaves, the electric field distribution (distribution within a plane in parallel with the surface to be processed) becomes uniform in the plasma where the microwaves are absorbed, and the sample can be uniformly processed.

A solenoid coil 91 and a solenoid coil 92 are arranged on the outer periphery of the circular waveguide 5 and the discharge block 3 and contained in a coil case 9. The

solenoid coil **91** generates a magnetic field more intense than that of the solenoid coil **92**, and their magnetic field intensities are controlled by a controller **93** connected to the solenoid coils **91** and **92**. The coil case **9** is mounted on the circular waveguide **5** and on the discharge block **3**, and the upper portion thereof above the discharge block **3** can be separated as one unit from the base flange **2**. The upper portion above the discharge block **3** is attached or detached by a lift means that is not shown. A cooling gas feeding port **94** is formed at a lower portion of the coil case **9**, a ventilation hole **54** is formed at a lower portion of the circular waveguide **5**, and a cooling gas such as nitrogen gas or the air is fed into the coil case **9**. The cooling gas fed into the coil case **5** flows through the ventilation hole **54** and is discharged to the open air through the waveguides **5**, **51** and **52**.

The base flange **2** is provided with a processing gas feeding port **21**, and a gas feeding passage is formed leading to gas blowing ports **32** via a gas communication passage formed in a portion where the flange **2** is fitted to the discharge block **3** and a gas pipe formed in the discharge block **3**. It is further possible, for example, to place a quartz plate having gas blowing ports under the microwave introduction window **4** made of a quartz plate, so as to introduce a processing gas into the space between the quartz plate and the microwave introduction window **4**, and to blow the processing gas from the upper portion of the discharge block **3** (not shown). By this arrangement along with the tapered inner surface of the discharge block **3**, the replacement of an old processing gas with a new processing gas in the discharge block **3** can be promoted. Accordingly, the reaction products are easily discharged out of the discharge block **3**, and the etching rate and the uniformity are further enhanced. The gas communication passage formed in the portions where the base flange **2** is fitted to the discharge block **3** is established when they are combined together.

On the bottom portion of the processing chamber **1** is provided, via an insulating material **7**, a sample stage **8** on which a wafer **10**, a substrate to be processed, is placed concentrically with the axis of the discharge block **3** provided on the upper portion. To the sample stage **8** is connected an RF power source that is not shown so that a bias voltage can be applied thereto. At the central portion of the sample stage **8** is provided a wafer push-up **81** for sending and receiving a wafer **10** to and from a known conveyer means such as a robot arm that is not shown when the wafer **10** is placed on the sample plate **8** or is removed from the sample plate **8**. A lift drive unit **82** is provided at the lower end of the wafer push-up **81** to move the wafer push-up **81** up and down. The lift drive unit **82** is firmly supported by a support member **83** that is attached to the lower portion of the sample plate **8**. Moreover, a lift drive unit **84** is provided at the lower portion of the support member **83** to move the sample stage **8** up and down. The lift drive unit **84** is firmly supported by a support member **85** attached to the lower portion of the processing chamber **8**. A spiral coolant passage **86** is formed in the sample stage **8** and is connected to a coolant feeding port **87** and to a coolant recovery port **88** that are formed in the support member **85** via piping.

In the thus constituted microwave plasma etching device, the sluice valves **18** are lowered by the lift drive units **19** in a state where the wafer is introduced into a load lock chamber (not shown) and is kept in a vacuum condition by known technology, and the wafer is introduced into the processing chamber **1** by a transfer arm (not shown). In this case, the sample stage **8** is lowered by the lift drive unit **84**, and the wafer push-up **81**, too, is lowered by the lift drive unit **82**. When the transfer arm which has placed the wafer is halted at the upper part of the sample stage **8**, the wafer push-up **81** is raised by the lift drive unit **82** to receive the wafer from the transfer arm. After the wafer is transferred onto the wafer push-up **81**, the transfer arm returns back to its retracted position. The sluice valves **18** are then raised and a hermetically closed space is defined in the processing chamber **1**. The interior of the processing chamber **1** is then evacuated by the evacuation means.

After the transfer arm has retracted, the wafer push-up **81** is lowered, and the wafer **10** is placed on the upper surface of the sample stage **8**. Thereafter, the sample stage **8** is raised by the lift drive unit **84** to a predetermined position necessary for plasma processing. In this case, while the sample plate **8** is being raised, the upper peripheral surface of the wafer **10** that is being raised comes into contact with the wafer holder **19** that is placed on the support of the processing chamber **1**, and the wafer holder **19** is lifted up. Thus, the wafer **10** is supported on the upper surface of the sample stage **8** by the own weight of the wafer holder **19** (or being pressed by a spring force). Here, the wafer **10** may be supported on the upper surface of the sample stage **8** by utilizing an electrostatic attracting force in place of using the wafer holder. A cooling medium such as cooling water is supplied from the coolant feeding port **87** to the coolant passage **86** in the sample stage **8**, and the sample stage **8** is kept at a predetermined temperature. Different coolant can be selected depending upon the temperature of the sample stage to be cooled.

In evacuating the interior of the processing chamber **1** by the evacuation means prior to feeding the processing gas, when a predetermined pressure is detected by the pressure detector **17**, the valve **16** is closed to isolate the pressure detector **17** from the atmosphere in the processing chamber **1**. This makes it possible to protect the pressure detector **17** from the processing gas and the reaction products during the processing, and to accomplish correct detection at all times when necessary. Next, the processing gas is fed from the gas feeding port **21**, the pressure in the processing chamber **1** is detected by a diaphragm vacuum gauge (not shown) while uniformly introducing the processing gas into the discharge block **3** through the plurality of gas blowing ports **32** that are evenly formed, and the pressure in the processing chamber **1** is controlled to acquire a predetermined value by the pressure control valve **12**. In the discharge block **3**, in this case, the processing gas is uniformly introduced from the upper portion of the discharge block **3** toward the center thereof, and is uniformly diffused in tapered space in the discharge block **3** before it is exhausted in a way from the upper side toward the lower side, making it possible to enhance homogeneity of the plasma that is produced.

When the pressure in the processing chamber **1** reached a predetermined value enough to execut the processing, microwaves are generated from the microwave oscillator **6** and are introduced into the discharge block **3** through the circular waveguide **5** and the microwave introduction window **4**. Here, the impedance matching for the microwaves, introduced into the circular waveguide **5** through the rectangular waveguide **52** and the rectangular-circular conversion waveguide **51**, is established by the space in the enlarged circular waveguide **5** and by the microwave tuning plate **53**, whereby a uniform and strong electric field is created and is introduced into the discharge block **3** through the microwave introduction window **4**. The discharge block **3** is heated by the heater **33** and is kept at a predetermined temperature by the controller **34** while detecting the tem-

perature by the temperature detection means (thermocouple) that is not shown. The solenoid coils **91** and **92** are supplied with electric power from the controller **93** so that magnetic fields of predetermined intensities are generated, and magnetic fields are so generated as to form a planar ECR electron cyclotron resonance plane in the discharge block **3**. Due to the introduction of microwaves into the discharge block **3** and formation of the magnetic field in the discharge block **3**, the processing gas in the discharge block **3** turns into a plasma upon receiving the ECR action. The plasma is generated uniformly at a high density owing to the electric field from the circular waveguide **5** that is uniformly intensified by the action of the microwave tuning plate **53**. The microwave tuning plate **53** has a shape that is best suited for the impedance matching of the microwaves in the circular waveguide **5**, and the microwaves in the circular waveguide **5** are uniformed and efficiently introduced into the discharge block **3**.

The wafer **10** is uniformly processed with a plasma which is generated in the discharge block **3** and has a uniform, high density. As a material to be processed, for instance, an aluminum alloy (Al—Si—Cu in this case) was processed by using an etching gas of $BCl_3+Cl_2+CH_2F_2$ (200 sccm at a flow rate ratio of about 6:7:1) under the conditions of a processing pressure of 0.012 Torr and a microwave power of 1000 W (2.45 GHz), the uniformity was about 4% when the microwave tuning plate **53** was used, which was about twice as good as the uniformity about 9% of when the microwave tuning plate **53** was not used. In this case, the uniformity of only the active species in the plasma was evaluated without applying an RF voltage to the sample plate **8**.

In processing the wafer **10** with a plasma as described above, a position at which the ECR plane is formed by controlling the electric power supplied to the solenoid coils **91** and **92**, is brought close to or away from the wafer **10** in order to change the amount of ions in the plasma incident upon the wafer **10** and to select low-damage processing, high-speed etching processing or selective etching.

Furthermore, a strong magnetic field is established by solenoid coils **91** and **92** to expand a resonance region with the microwave electric field in the form of a plane, the distance between the surface of the sample to be treated and the plane of the resonance region that are in parallel is changed when the sample is processed and when the sample is over-etched, and the position of the plasma that is generated by the actions of the electric field produced by the microwaves and by the magnetic field produced by the solenoid coils is changed. For example, the position of the plasma is moved away from the surface of the sample when it is to be processed to prevent the formation of residue at the time of etching the sample and the position of the plasma is moved close to the surface of the sample at the time of over-etching the sample, thereby to suppress the rate of etching of the underlying material at the time of over-etching the sample.

In processing the wafer **10** with a plasma as described above, $AlCl_3$ which is a reaction product tends to adhere to the inner wall of the discharge block **3** which is the plasma-generating chamber. By heating the discharge block **3** at about 120° C., however, the reaction products that tend to adhere to the wall surfaces in the discharge block **3** are heated and vaporized. That is, reaction products do not adhere to the inner wall surfaces of the discharge block **3** but are exhausted. Therefore, the processing with a plasma is free from change with time. During the processing with a plasma as described above, the discharge block **3** is heated at a temperature at which the reaction products vaporize.

A protective member such as of alumina, mullite or quartz and, in this case, a protective film **31** which is made of a plasma-resistant material, is formed on the inner wall surfaces of the discharge block **3** exposed to the plasma. Even when the discharge block **3** made of aluminum is similar to the material of an aluminum alloy to be processed, therefore, the discharge block **3** is protected from the plasma with which the material to be processed is etched.

After the etching of the wafer **10** that is executed as described above is finished, supply of the processing gas for etching, microwave power and RF power is stopped. The sample stage **8** is then lowered and the wafer is transferred out through the steps reverse to the steps of introducing the wafer. After the wafer is transferred out, the gas is replaced by a processing gas for cleaning. For instance, a gas for plasma-cleaning such as 0_2 or 0_2+SF_6 is introduced into the discharge block **3**, and a plasma is generated in the same manner as when the etching is effected without placing a wafer **10** or dummy wafer on the sample stage **8** and without applying the RF voltage to the sample stage **8**. After the plasma-cleaning is executed for about ten seconds, a new wafer is subjected to the etching in the same manner as described above. The plasma-cleaning without any wafer is most effective when it is executed after one wafer is processed. In practice, however, the controller that controls the processing apparatus is set to execute the plasma-cleaning of every two, three, or "n" wafers, etc., to meet the overall throughput, and the processing apparatus automatically executes the cleaning. Therefore, the cycle of plasma-cleaning that had, so far, been done for every lot every about 30 minutes by using a dummy wafer can be lengthened to four to 10 times or longer. Furthermore, the cycle of wet-cleaning in which the processing apparatus is opened to the air for a whole day every a week can be lengthened to two to three weeks or longer, contributing to greatly enhancing the throughput. Even the plasma-cleaning without a wafer can be executed without affecting the sample stage **8** since the processing time is short and a protective coating such as an Alumite coating is applied to the surface of the sample stage **8** on which the wafer is placed.

During the cleaning, furthermore, an inert gas such as N_2 or He that does not affect the process may be blown into the gap in which the wafer push-up **81** is provided from the lower side toward the upper side to blow dirt and dust staying in the gap in which the wafer push-up **81** is provided, in order to further enhance the cleaning effect.

The above-mentioned effects can similarly be obtained in regard to improvement of the throughput even when the solenoid coils **91**, **92** and the controller **93** are omitted and even in the case of another processing apparatus using a plasma.

In opening the discharge block **3** to the air, furthermore, there is no need of disconnecting the gas piping and the like since the gas passage is formed between the discharge block **3** and the base flange **2**. Moreover, the discharge block **3** and solenoid coils **91**, **92** that are integrally constituted in the coil case **9** can be removed as one unit from the base flange **2**, facilitating the cleaning operation, inspection and repairing work.

By employing a hot valve that can be heated between an auxiliary pump such as a rotary pump and a high-vacuum pump such as a turbo molecular pump **13** of the evacuation means, furthermore, it is possible to prevent the pressure from increasing on the exhaust side of the high-vacuum pump and, hence, to prevent the reactive products from adhering, which leads to an improved reliability of the evacuation means.

Another embodiment of the present invention will now be described with reference to FIGS. 2 and 3. In FIG. 2, the same portions as those of FIG. 1 are denoted by the same reference numerals and their description will be not repeated.

In this embodiment, a slot antenna 41 provided on the bottom surface of the waveguide 5A is radially arranged with respect to the center axis of the resonator as shown in FIG. 3 in order to emit a circular TE_{01} mode. In this case, the microwaves emitted from a plurality of slot antennas 41 are propagated through a waveguide 5B having a predetermined distance and are then formed as a whole into microwaves of the circular TE_{01} mode. A space is necessary between the slot antenna and the quartz window 4 through which the microwaves pass so that the microwaves emitted from the slot antenna can expand to a particular microwave mode, i.e., so that the microwaves emitted from the slot antenna 41 establish a particular microwave mode in the whole discharge tube 3A, i.e., in the plane. This space is formed by the waveguide 5B. The waveguide 5A and the slot antenna 41 are effective in stably forming microwaves of any mode, and a plasma is stably generated in the discharge tube 3A. By optimizing the distance between the quartz window 4 and the slot antenna 41, furthermore, there can be generated a uniform and highly dense plasma. Moreover, the waveguide 5A and the slot antenna 41 are so shaped as to emit microwaves of the circular TE_{01} mode that is axially symmetrical, and the microwaves of the circular TE_{01} mode are introduced into the discharge tube 3A to generate a uniform plasma.

By changing the shape of the slot antenna, furthermore, the microwaves of another mode can be introduced into the processing chamber. By changing the plasma density, it is allowed to feed a plasma that is best suited for the material that is to be processed.

As described above, the embodiment exhibits a variety of actions and effects, and the generation of a uniform and highly dense plasma helps further improve uniformity and processing ability in the processing of wafers with a plasma. Moreover, the processing with a plasma can be carried out maintaining a good performance independently of the material to be processed, and can be stably continued maintaining a state of good processing ability.

With respect to the above embodiment, the etching of an aluminum alloy was described as an example. However, the object to be etched is in no way limited thereto but may be a variety of materials such as metals, gates, oxides and the like. The invention can be adapted not only to the etching processing but also to other processings with a plasma such as film-forming processing and the like.

Concerning the uniformity, the same action as that of the above embodiment is obtained even in the case where the solenoid coils 91, 92 and the controller 93 in FIG. 1 are omitted, and uniformity in the processing can be improved.

The present invention makes it possible to produce a high-density uniform plasma, thereby to further improve the processing performance, to execute the processing with a plasma maintaining a good processing performance independently of the material to be processed, and to stably execute the processing with a plasma in a state in which good processing performance is maintained.

What is claimed is:

1. A plasma processing method wherein:

a first substrate to be processed is processed with a plasma in a processing chamber, in which the plasma is generated;

after said first substrate to be processed is processed with a plasma and is transferred from the processing chamber, the interior of said processing chamber is cleaned with a plasma without placing any further substrate to be processed on a sample stage in the processing chamber, whereby cleaning is performed without any substrate on the sample stage in the processing chamber, the sample stage including a member that protects the sample stage from damage due to the plasma during the cleaning, and wherein during the cleaning an inert gas is blown into a gap, at the sample stage, in which a wafer push-up is provided, to blow away contaminants in the gap;

a next substrate to be processed, after said first substrate, is introduced into said processing chamber after the cleaning with a plasma has been finished; and

said next substrate to be processed is then processed.

2. A plasma processing method wherein:

a first substrate to be processed is processed with a plasma in a processing chamber in which a plasma is generated;

after said first substrate to be processed is processed with the plasma, said first substrate is transferred from the processing chamber, and thereafter the interior of said processing chamber is cleaned with a plasma without placing any further substrate to be processed on a sample stage in the processing chamber, so as to perform plasma cleaning, whereby the cleaning is performed without any substrate on the sample stage in the processing chamber, wherein said sample stage is cleaned during the plasma cleaning within the processing chamber, and wherein during the cleaning an inert gas is blown into a gap, at the sample stage, in which a wafer push-up is provided, to blow away contaminants in the gap;

then a next substrate to be processed, after said first substrate, is introduced into said processing chamber, after the cleaning has been finished; and

said next substrate to be processed is then processed.

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